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ANALYSIS OF FORMING TREAD WHEEL SETS

Summary. This paper shows the results of a theoretical study of profile high-speed grinding (PHSG) for forming tread wheel sets during repair instead of turning and mold-milling. Significant disadvantages of these methods are low capacity to adapt to the tool and inhomogeneous structure of the wheel material. This leads to understated treatment regimens and difficulties in recovering wheel sets with thermal and mechanical defects. This study carried out modeling and analysis of emerging cutting forces. Proposed algorithms describe the random occurrence of the components of the cutting forces in the restoration profile of wheel sets with an inhomogeneous structure of the material. To identify the statistical features of randomly generated structures fractal dimension and the method of random additions were used. The multifractal spectrum formed is decomposed into monofractals by wavelet transform. The proposed method allows you to create the preconditions for controlling the parameters of the treatment process.

1. INTRODUCTION

Despite regularly conducted research in the field of improving the operational capabilities of wheel sets and rail tracks, every year, in the world, tens of millions of railway wheels are resized using tread machining. In [1] classification methods are provided for the rim profile wheel machining. The preferred methods are turning, mold-milling, cutting profile high-speed grinding (PHSG), and combined treatments. Combined methods include mechanical and physical treatments (e.g. local laser hardening, induction thermal-cycling after reprofiling, and so on).

The most common practice, nowadays, is turning and mold-milling. For example, the Danobat underfloor wheel lathe is a specific machine tool for the corrective maintenance of railway rolling surfaces and train brake discs [2]. It can perform without the need for dismounting the train axle and is equipped with the latest technology. The Stanray TM Underfloor Wheel Truing Machine (TN-84C) [3] is an underfloor pit-mounted milling machine capable of simultaneously reprofiling both wheels of a railway wheel set using the axle centers as the machining reference point.

A significant disadvantage of these methods and their technological schemes is the low capacity of the tool to adapt to the inhomogeneous structure of the wheel material being processed. This leads to understated treatment regimens, difficulties to recover wheel rims with thermal and mechanical defects, and increased tool wear. The current direction is to develop new and improved methods of processing wheel sets with inhomogeneous structure of the material. The aim is to make recommendations for improving tool life. Research in the field of improving mold-milling [4 - 6] showed positive results: that is, an increase in tool life by 1.5–2 times. In [7] the efficacy of combined technological schemes using local power plunge grinding is indicated. At the same time, in [1], significant improvement of the machining tread wheel during its operation and manufacturing allows

PHSG. The economic efficiency of the process is because of PHSG: that is, there is no need for cutting the useful layer of the wheel rim, low roughness of the treated surface, and high-production. However, the potentially promising method of machining using PHSG is currently not widely implemented because of the need for theoretical and experimental study.

Comprehensive study of PHSG and development of new technological schemes for implementation and management of its technological parameters will improve the practical application of the method of machining, which, potentially, has high efficiency.

Methodology of scientific research to improve practical application of the PHSG method assumes the following:

- development of mathematical mapping and kinematic cutting patterns for definition of parameters of the shear layer and the variation of the kinematic angle of the cutting blades;
- modeling and analysis of emerging cutting forces based on the morphogenesis of the accepted model and kinematic parameters of the shear layer;
- development, justification, and use of algorithms describing the random nature of the components of the cutting forces;
- study and application of phenomenological methods to describe supposedly emerging and not fully studied processes in PHSG, to develop technology management schemes;
- development of a methodology of experimental studies and practical recommendations for its implementation.

2. DEVELOPMENT OF ALGORITHM, SIMULATION, AND ANALYSIS OF THE PHSG PROCESS

A tool to perform PHSG (shaped grinding wheel) [7] was proposed to be interpreted as a milling cutter, working on a generator cutting scheme. This interpretation allows us to analyze the kinematics of the tread wheel sets using PHSG based on the method developed in [8], to perform generalized mathematical mapping, to study the kinematics of the cutting surface of riding wheel sets, and to define the parameters of the shear layer applied in a similar manner [9].

A distinctive feature of the molded grinding wheel and molded cutter is cutting the number of individual elements (Fig. 1). The number of cutting elements for the grinding wheel can be defined as the ratio of the forming curve to the average size (diameter) of the grain of the grinding wheel. Deviation of the grain geometry and size from the average size is neglected because of their smallness compared with the diameter of the cutting tool, defining the main motion vector and a scalar of cutting speed value.

The complexity of describing the cutting blade edge tool for PHSG and the kinematics for the formation process cause considerable difficulty in determining the cutting forces. The problem is solved by applying geometric fractals [10, 11], using the process of mold-milling in [8] for analogy.

The shape kinematics of the molded cutter is identical to that of the processing disk mill without longitudinal feed. In this case, the longitudinal feed is realized by generating cutting patterns. Simulation of the process of shaping the nominal surface wheel sets to expedient make with a mathematical cutting patterns that including not only such the cutting parameters as the major move of machining, feed movement, kinematic changes in the angles of the cutting tool but the ability assess their at any point in the treatment area, which depends on workpiece material and condition of individual sections of the surface material of the tool and its physic-chemical characteristics.

To describe the process of cutting the material of the tread wheel with inhomogeneous structure, the cutting force is decomposed into two components: deterministic and random.

The deterministic component is uniquely defined based on morphogenesis kinematics and is calculated by the method described in [9], provided that the treatment in the delivered condition has constant hardness in the cutting zone.

The random component of the cutting force when processing the tread wheel acts on the distribution of the surface hardness of the tread wheel and, as a result, is determined by changes in the structure of its material. Therefore, the random forces of the processing wheel sets with thermomechanical damage carry with it the statistical properties of the material structure. It is permissible to assume that the random force is fractal, as is the distribution of the surface hardness of the tread wheel.

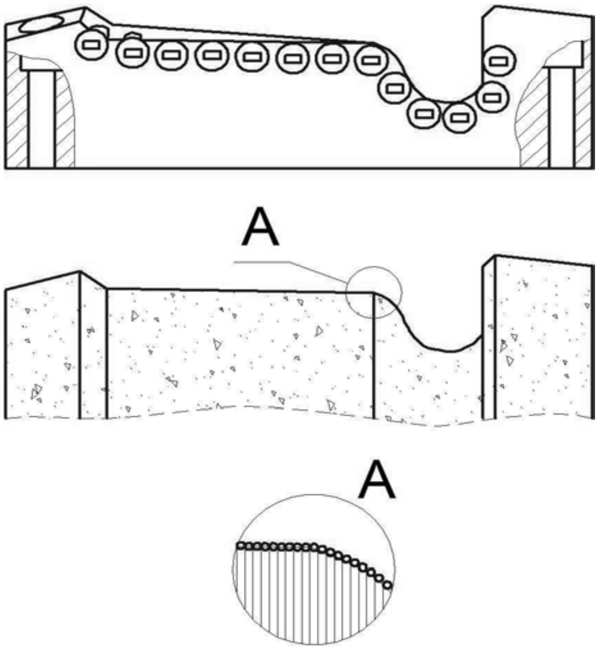

Fig. 1. Analog of the cutting part of the molded cutter and grinding wheel

It should also be noted that the random component of the cutting force is also affected by defects discontinuity: that is, by cracks that can cause shock loading on the blade of the tool. Wheel sets with such defects in operation are not allowed and their processing is performed only under the "skin", which is not relevant for this method of treatment. Therefore, in this case, the pattern of distribution of defects such as discontinuities in the modeling of the random component of the cutting force can be neglected.

As can be seen from studies carried out in [9], the actual cutting force can be described by the following equation:

$$P(t) = P_k(t) \cdot \left(\frac{HB(t)}{HB_k}\right)^n = P_k(t) \cdot \left(A(t)\right)^n, \tag{1}$$

where P(t) and Pk(t) are the cutting forces in the surface treatment with a variable hardness and strength, a certain forming kinematics, respectively; HB(t) and HBk are varying surface hardness in the cutting zone and the hardness of the material as supplied, respectively; A(t) is the coefficient of variation of the relative surface hardness.

To interpret the random cutting force it is necessary to calculate the fractal dimension amplification factor from formula (1) and to determine the range of their changes. Fractal dimension allows to reveal statistical features in a randomly generated structure.

To determine the fractal dimension of the time series, in practice, the most applicable method is rescaled range using the dependence of the fractal dimension of the Hurst exponent [11]:

$$D = 2 - H, \tag{2}$$

where D is fractal dimension of the set; H is the Hurst exponent.

Hurst exponent for the set can be approximated by calculating the slope of the line through a simple method of least squares regression. In particular,

$$\ln\left(\frac{R}{S}\right) = \ln(c) + H \cdot \ln(n), \tag{3}$$

where R is the difference between the maximum and minimum accumulated deviation; *S* is standard deviation; $\frac{R}{S}$ is normalized scale; *c* is a measure of correlation; *n* is number of observations.

For the interpretation of the cutting force it is necessary to simulate a numerical amplification factor from formula (1). For modeling, fractal structure can be effectively applied to the method of random additions [12, 13].

The algorithm, which is incorporated in the method of random additions, is the assertion that the variance of the increment coordinates on each subsequent iteration must satisfy the following equation:

$$\sigma_i^2 = r^{2(2-D)i}\sigma_0^2, \tag{4}$$

where *r* is zoom factor; σ^2_0 is initial dispersion of random additions, $\sigma^2_0=1$; *D* is generated fractal mension of the set; *i* is the number of iterations.

This algorithm involves the use of a sample from a normal distribution. It is known that the dispersion of normal random values is the sum of variances of these quantities. Therefore, dispersion of the generated plurality after any number of iterations is equal to the sum of the variances of all iterations:

$$\sigma^2 = \sum_{i=0}^{k} \sigma_i^2. \tag{5}$$

Frequency characteristics of the modeled structure and the random component of the load are identical. In the random component of the cutting force, the composition frequency can limit the importance of the contribution the components of the frequency spectrum. The frequency spectrum of a simulated set is also finite and is characterized by the number of iterations. From the analysis of formulas (4) and (5) it is evident that with an infinite number of iterations (frequency spectrum) variance approaches a finite value. As shown by the graphs (Fig. 2), the dispersion after a small number of iterations is not very different from the limit. Accordingly, for effective modeling, it is sufficient to perform the number of iterations that will provide a sufficiently close approximation of the dispersion limit. For the median value D=1,5 from the interval describing $D \in (1;2)$, the possible fractal dimension, a sufficient number of iterations is about *k*=9 (Fig. 2), which corresponds to the number of points of the set $2^k=2^9=512$.

Sets obtained by random additions are multifractals with the spectrum of fractal dimensions in the area specified in the modeling of the central fractal dimension.

To identify the random component of the cutting force it is necessary to select a monofractal that will carry the basic statistical properties of a multifractal with a uniquely defined dimension. In this case, it will be the maximum dimension of the spectrum of fractal dimensions and close to the central dimension multifractal [14].

Wavelet transform with its hierarchical basis is well adapted for the analysis of fractal and multifractal sets with a hierarchical nature [15]. The result of the wavelet transform one-dimensional array is a two-dimensional array of the amplitudes of the wavelet transformation: coefficient values *W(a, b)*. The distribution of these values in the space *(a, b) = (time localization, the time scale)* gives information about the evolution of the relative contribution of various components of the time scale.

Expanding the multifractal on levels using wavelet transform, it is necessary to determine the level with the highest fractal dimension and select the corresponding array that will, with sufficient precision, describe the gain of formula (1) and, as a consequence, statistically describe the cutting force.

When processing using c-molded tool the perimeter of the cross section of the tread wheel was simultaneously formed; therefore, measuring the fractal dimension of the gain *A* in the calculation of the cutting force can serve as the arithmetic mean of fractal dimensions obtained for the five specific sections of the tread wheel. In the particular case given in [11], the fractal dimension is of *1,6*.

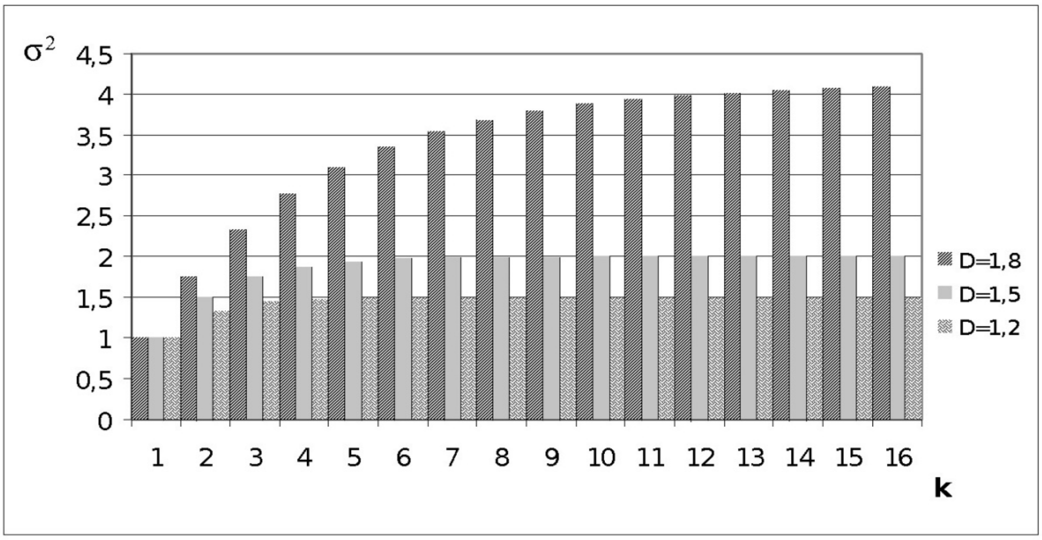

Fig. 2. Dependence dispersion σ^2 of simulated sets the number of iterations *k*, for different values of the fractal dimension *D*

For the formation of a change rate of relative hardness, a fractal species with a limited range of frequencies forms the multifractal specified dimension on the basis of random additions (Fig. 3). Next, the decomposition is obtained as a multifractal spectrum from monofractals using wavelet transform (Fig. 4).

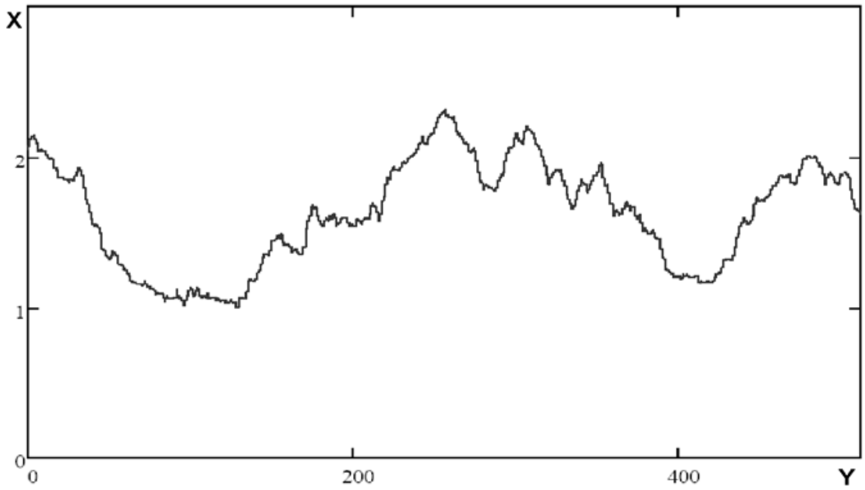

Fig. 3. Multifractal specified fractal dimension $D = 1,6$, formed by random additions in 2D x, y

The fractal dimension monofractals obtained from the wavelet-spectrum by decomposition of the levels of *a* is defined (Fig. 5, 6). For a monofractal with a maximum (central) dimension, the array of points forming it is defined.

The above-described method allows to form the prerequisites for controlling the parameters of processing, in particular, the feed (in this case, the longitudinal feed is realized by generating cutting patterns) – and the speed affects the thickness of the shear layer – and, also, to predict the changing cutting forces under the action of the thermomechanical damage.

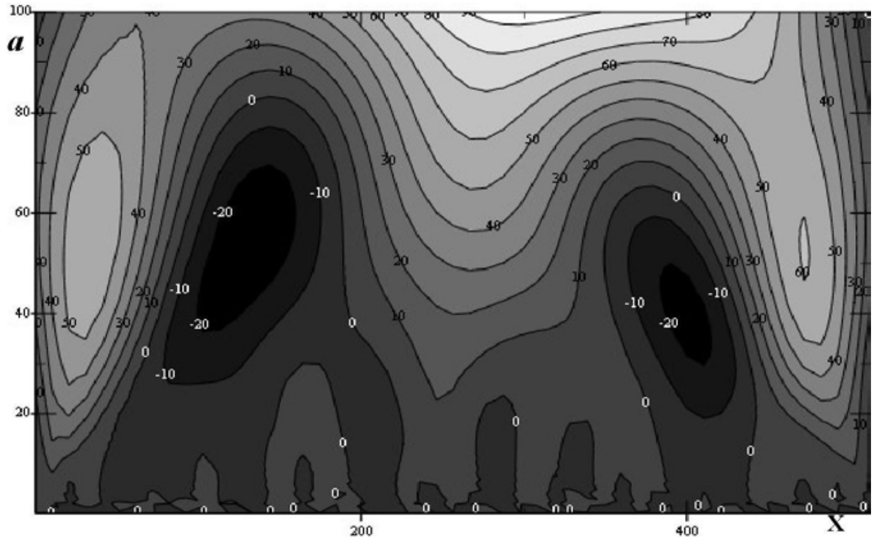

Fig. 4. The wavelet spectrum for multifractal shown in Fig. 3 in levels *a*

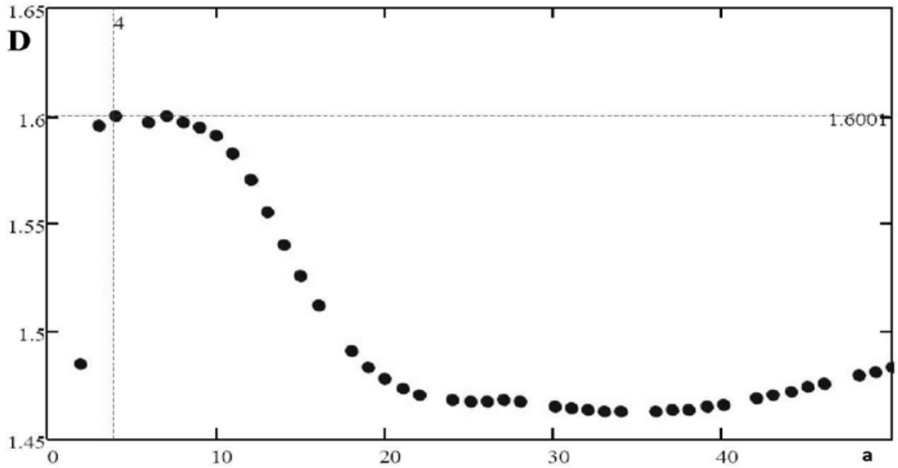

Fig. 5. The spectrum of fractal dimensions of a multifractal is shown in Fig. 3. Maximum fractal dimension *D=1,6* for the level of *a=4*

Formulated in [5] are the principles of self-adapting the tool to the processing conditions applied in the design and description of ways to control the influence of the random component of the cutting force on the quality of the process PHSG. In particular, the above-described randomly initiated fractal species in the system of machine tools can be administered to additional structural elements, improving the efficiency of the conditions of large damping at low-frequency settings.

3. PREDICTION PROCESSES ALLOWING TO IMPROVE THE MANAGEMENT OF WHEEL PAIR MORPHOGENESIS

It should be noted that the implementation of the method of PHSG can give rise to cutting speeds at which the process of over cutting can occur. As referred to, this process is characterized by reduced cutting forces due to probable formation of the cutting zone in the superfluid state of matter under the influence of a powerful influence of power. Moreover, this process is accompanied by intense heat-out from the cutting zone. At the same time, [16] states that the experimental treatment of steel with high strength and hardness in the range of high-speed processing feed has a stronger effect on the removal of heat from the cutting zone than does the cutting speed. Although by increasing the cutting speed heat cutting volume permanently increases, when a large feeding part enters into the workpiece for heat cutting, it decreases proportionally, but the surface cutting temperature of the workpiece also decreases. For the purpose of investigating such phenomena, one can use the technique described in [17].

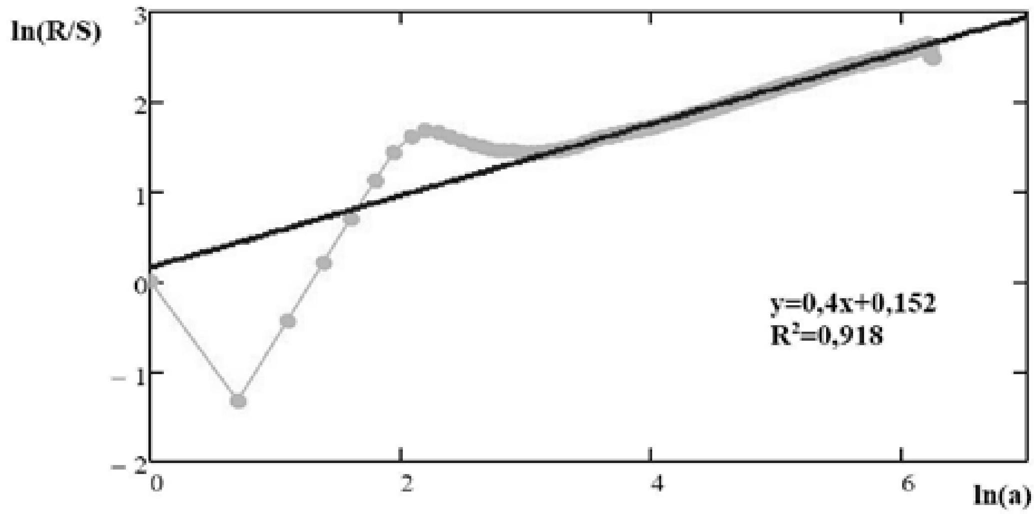

Fig. 6. Graph for the determination of the fractal dimension of a monofractal, a dedicated wavelet spectrum to the level of *a=4*. The fractal dimension *D=2-0,4=1,6*

4. CONCLUSION

1. The disadvantages of the methods of turning and mold-milling employed for forming tread wheel sets during repair are noted.
2. The results of a theoretical study of PHSG for forming tread wheel sets are presented.
3. In the process of rebuilding the wheel profile with an inhomogeneous structure, the emerging cutting force is proposed to be decomposed into two components: deterministic and random.
4. To identify the statistical features of randomly generated structures, the authors used fractal dimension and the method of random additions and the resulting multifractal spectrum is decomposed into monofractals by wavelet transform.
5. Economic efficiency of the process is because of PHSG: no need for cutting useful layer of the wheel rim, low roughness of the treated surface, and high production.

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